Predicting Upwelling Radiance on the West Florida Shelf

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LONG-TERM GOALS

The prediction of inherent optical properties [IOPs] and water-leaving radiance [L_w] in coastal waters over a 5 to 10 day time horizon will require a numerical simulation that accurately forecasts the physical, ecological, and optical environment. Critical to the ecological and optical forecast is the ability to directly compare the water-leaving radiance field to those being collected by aircraft and satellite platforms. Our goal is to develop the ecological and optical models and computer codes to initialize, validate, and predict the IOPs and L_w over an operational time horizon.

OBJECTIVES

1) Couple EcoSim 2.0 to a robust radiative transfer model to yield water-leaving radiance for a given IOP distribution

2) Initialize and validate spectral water-leaving radiance with remote sensing data.

3) Couple EcoSim 2.0 to the WFS version of the Regional Ocean Modeling System (ROMS)

APPROACH

The pace of development of prognostic ecological/optical data and modeling systems has greatly accelerated in recent years such that we can now reasonably discuss the likelihood of predicting red tides, and concomitant impacts on water clarity on the West Florida Shelf (WFS). Accurate prediction of water clarity and color suggests a fundamental knowledge of marine ecological systems, and the validation of such data and modeling systems would provide characterization of the littoral environment over operational time horizons. Water clarity and color are directly dependent on the IOPs of the water column and the modeling component of these prognostic systems requires a fundamental set of equations that describe the interactions between the production and destruction of the IOPs. As the IOPs of absorption, scattering, and the scattering phase function can be described by a summation of the individual components, the cycle of color can be described by equations representing the individual active color constituents, i.e., phytoplankton, organic detritus, Colored Dissolved Organic Matter (CDOM), sediments, bathymetry, and bottom classification. The description of the cycling of each component allows for feedback effects between the in-water light field and the production and destruction of color.

The marine optical environment may change at the same time scale of weather change, so any operational prognostic optical system would need to be embedded into a larger system of data collection and numerical modeling. Such a system would use moorings, ships, Autonomous Underwater Vehicles (AUVs), satellites, and physical/ecological/optical numerical models to provide integrated data streams to a wide community of users. The systems would need to be able to assimilate data as it became available, and provide forecasts over a wide range of time and space scales. The West Florida Shelf (WFS) is an ideal location to help develop these nowcast/forecast systems, in part due to a large number of other research programs focused on the WFS, including other ONR funded technology programs, NOAA/EPA ECOlogy of Harmful Algal Blooms (ECOHAB) program, and the State of Florida Coastal Ocean Monitoring and Prediction System (COMPS) program. The ECOHAB and COMPS programs are focused on time scales ranging from months to years and spatial scales ranging from kilometers to 1000s of kilometers. Therefore, this site provides a natural location to develop broad scale time and space models of the inherent optical properties.

The WFS is unique in other ways that make it ideal for the development of forecasting systems. In particular, the variance in color and clarity of the near-shore waters is extreme, ranging from oligotrophic Case 1-type waters to highly attenuating Case 2 waters (Bissett et al., 1997; Carder and Steward, 1985; Carder et al., 1989). The low-nutrient and low-colored waters of the WFS are derived from the oligotrophic waters of the central Gulf of Mexico and the waters of the Caribbean Sea via the Loop Current. These waters have typical open ocean color signals. In the deeper waters off the shelf, the variations in surface color are driven by seasonal nutrients and CDOM introductions via deep mixing, as well as eddy fluxes, much like the classic understanding of Case 1 ocean color. As one moves across the shelf break onto the outer shelf, complications to the classic blue ocean signal arise from both Loop Current intrusions that bring higher nutrient waters (and CDOM) into the euphotic zone and river CDOM fluxes from the Mississippi, Mobile, and Apalachicola Rivers. In the inner shelf, the color signal becomes even more complicated as the introduction of waters from Suwannee, Hillsborough, Peace, and Caloosahatchee Rivers mix with the above water masses, as well as with those waters created locally from high energy mixing (waves, long-shore currents, etc.) and heat flux imbalances.

The ecological/optical conditions on the WFS are as complicated as any coastal region, yielding situations where the chlorophyll a biomass may range from 0.01 to >20 μg liter^{-1} at the same location during different time periods. When oligotrophic waters dominant the shelf, bottom features are clearly evident in high-resolution hyperspectral data to a depth of 30 meters. At other times, river and estuary waters dominate, and the bottom is undistinguishable in waters <2 meters deep. In between these two conditions, the color signal is mainly a function of the ecological interactions between phytoplankton growth and loss and CDOM creation and destruction. Within the inner shelf, the color signal is further modified by the bottom classification and sediment re-suspension. Our goal on the WFS is to derive and validate a set of fundamental ecological/optical/physical equations that addresses, and eventually predicts, the complexity of the IOPs and the resultant water-leaving radiance. This site is an ideal location for the regional time and space scales being studied.

WORK COMPLETED

The work in FY2002 continued the integration of the radiative transfer code with the simulated IOPs from the EcoSim 2.0 (ES2) 2-dimensional WFS solutions. The previous work demonstrated the ability

to use simulated IOPs to generate Rrs(λ) spectra, however, computation speed and radiometric accuracy was an issue. In conjunction with Dr. C. Mobley (N0001497C0019 and N00014D01610002), we have integrated a very fast, radiometrically robust, radiative transfer code (Ecolight 4.1) with the ES2 IOP output IOP data stream. This code is now to be integrated into a 3-dimensional IOP simulation, and this work should be completed by Spring 2003.

In addition to the numerical coding challenges faced this year, the importance of the estuarine boundary condition became critically evident for predicting the cross-shelf IOP distribution (see also N00014-00-1-0411). The estuarine boundary condition includes not only the CDOM inputs, but also the nutrient and particulate loads to the near-shore environment. It was found that these nutrient inputs were critical in the prediction of particulate absorption and scattering, thus an accurate assessment of inputs was required. This assessment was used to establish the shore-ward boundary condition during periods of peak flows in the Fall of 1998. These fresh water and estuarine data sets are particularly sparse, and their collection required coordination with 8 different state and federal agencies. Frequently the data were inconsistent and required multiple cross-checks and repeat communication with the various agencies. However, all the water quality data from 1997 to 2002 from the Charlotte Harbor region has been assembled in an ArcView database and is available for distribution. This data set forms the basis for the shore-ward boundary condition in the ES2 2-dimensional simulation, as well as for the 3-dimensional runs to be generated in FY2003.

RESULTS

The terrestrial nutrient source hypothesis, which suggests that the intensification of biomass and IOPs in the near-shore environment on the WFS, has often been questioned because fresh water systems appear to be nitrogen limited on the West Florida Shelf. This appearance is the result of decades of measurements of the Dissolved Inorganic Nitrogen (DIN) to Dissolved Inorganic Phosphate (DIP) ratio of some terrestrial source waters, which are frequently below that which is considered necessary for balanced phytoplankton growth (mol DIN:mol DIP = 16:1). This has been particularly true for studies in the Charlotte Harbor region because the Peace River, which supplies >70 percent of the fresh water to the upper harbor estuary, frequently has DIN:DIP ratios <0.1. The cause of this extremely low value is that the Peace River drains the Hawthorne phosphatic formations, and frequently has DIP concentration that are an order of magnitude greater than the other rivers that supply fresh water to Charlotte Harbor. However, this apparent excess in phosphorus disappears if Total Nitrogen (TN), which also includes Dissolved Organic Nitrogen (DON) and Particulate Organic Nitrogen (PON), is considered as well as DIN. TN values can be orders of magnitude greater than DIN and may provide a source of nitrogen to the ecological system that directly, or indirectly, may be used by the phytoplankton community. Support for this supposition can be found in the high levels of ^{14}C productivity measurements in the Harbor when DIN is undetectable. TN to Total Phosphorus (TP) in the Peace River has been estimated to be ~16.

The Charlotte Harbor region can be divided into upper and lower estuaries (Figure 1). The fresh water of the upper estuaries is mainly supplied by the Peace and Myakka; the lower estuary is supplied by the Caloosahatchee River. The upper estuary is flushed mainly through Boca Grande Pass and around Pine Island, while the lower estuary is flushed mainly through San Carlos Bay. The lower estuary is much smaller in size and half as deep as the remainder of the Charlotte Harbor region, and as a result has an order of magnitude smaller volume associated with it (1.0×10^8 m^3 versus 1.3×10^9 m^3). Fresh water flows are greater through the Caloosahatchee River than the Peace River as it drains both the

Caloosahatchee River basin and Lake Okeechobee. The larger flows and smaller volume yield much smaller residence times for the fresh flow into the lower estuary compared to the upper estuary. In addition, the Caloosahatchee basin and Lake Okeechobee are not as impacted by the Hawthorne formations, and as a result the Caloosahatchee River has an order of magnitude smaller TP concentration than the Peace River, yielding a TN:TP ratio >25.

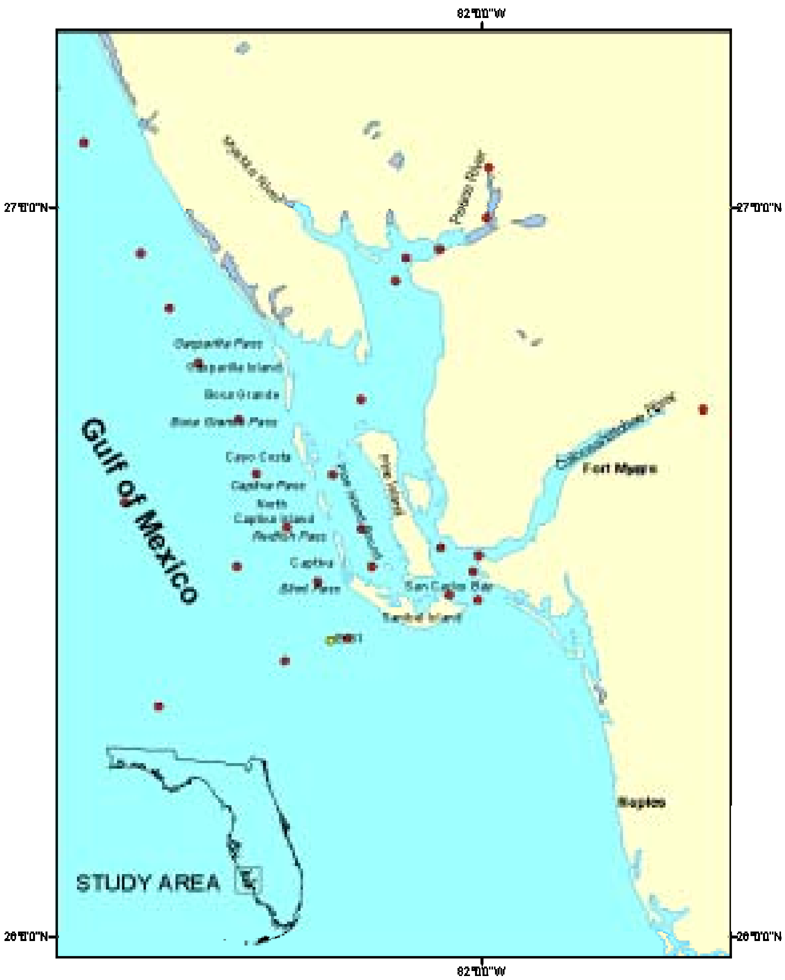

Figure 1. Study area and data stations in and around the Charlotte Harbor Estuary, Florida.

Flows from the Peace and Caloosahatchee River are frequently of similar size, however the shorter residence time of the Caloosahatchee estuary (lower Charlotte Harbor) both complicates and simplifies the calculation of total nutrient delivery to the shelf. The complications arise from the fact that modification of the nutrient during high water flow pulses during their transit through the lower will be far less than those in the upper harbor. In 2001, the water flows were sufficient to completely turn the entire lower estuary over twice in one week. Thus, one could assume very little modification of the particulate carbon, nitrogen, and phosphorus. However, with the longer residence times of the upper harbor, a large fraction of the water is delivered to the shelf with some indeterminate nutrient history. We have attempted to correct for these effects by collecting a large series of data from the rivers,

middle harbor, and near-shore environments and regressing the inorganic and organic nutrients against salinity (Figure 2). While the some spread in the data, it appears that the modification through the estuary of the total nutrient stocks is low and that a linear extrapolation is sufficient. Evidence for optical impacts of these high water pulse events can be seen in satellite, mooring, and ship data.

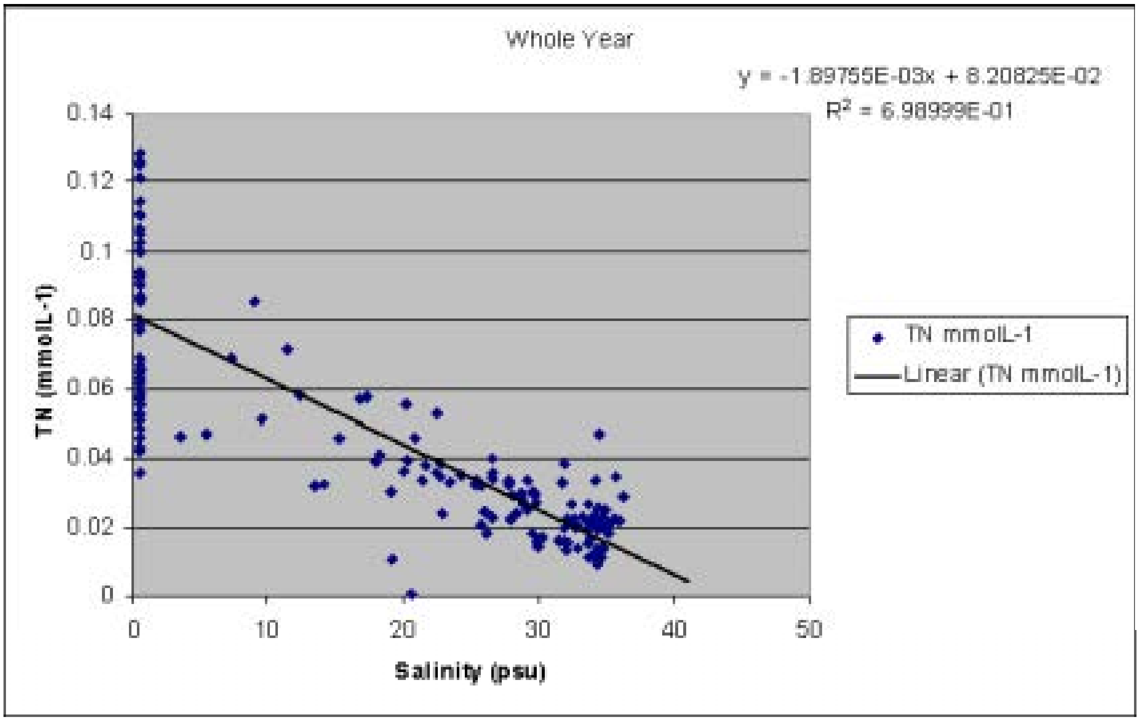

Figure 2. Total Nitrogen during 1998 and 1999 from West Florida Shelf/Charlotte Harbor region displaying a negative correlation between TN and salinity (y=-1.89755E-03x+8.20825E-02 R^2= 6.99E-01)

The biomass results of adding these nutrient pulses can be seen in Figure 3, where the total chlorophyll concentrations are greatly increased in the near-shore areas. This is matched by increase in chlorophyll seen in the SeaWiFS estimated chlorophyll (Figure 4 and 5).

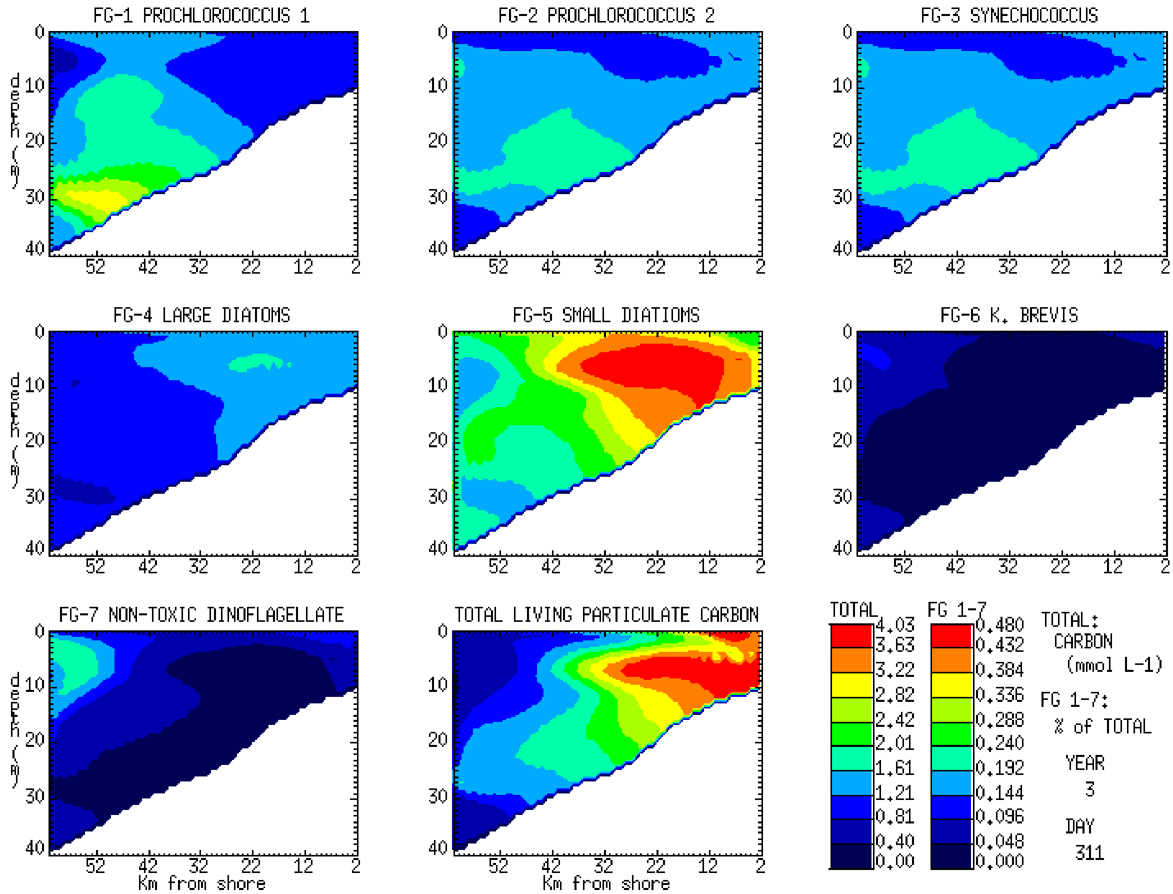

Figure 3. Predicted chlorophyll and functional group distribution for day-of-year 311 (November 7th). Prochlorococcus and Synechococcusare are present offshore (>32km from shore at a depth of ~15-30m). This region is mostly dominated by Prochlorococcus. Large and small diatoms are present nearshore, (~2-32km from shore and at a depth of ~0-20m). This region is almost entirely dominated by small diatoms. K. brevis is not present on the WFS. Non-toxic dinoflagellates are present offshore (>52km from shore and at a depth of ~0-10m). Total living particulate carbon is greatest in shallow nearshore waters (<32km from shore at a depth of <20m).

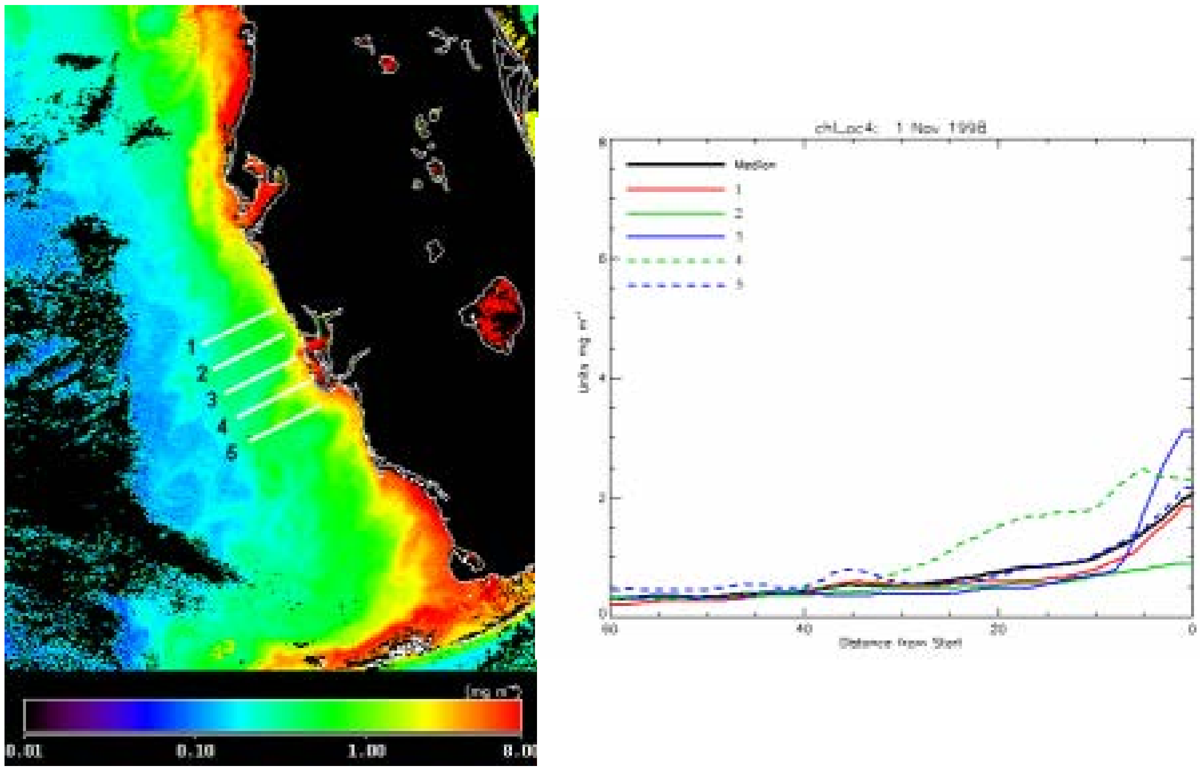

Figure 4. SeaWiFS estimated chlorophyll a concentration for the West Florida Shelf and selected transects on November 1, 1998. Maximal concentrations of chloropyll a are present in the region of the barrier islands surrounding Charlotte Harbor (~1.0 mgm^{-3}) with decreasing concentrations further offshore. The WFS has been divided into 5 parallel transects for analysis. These transects are interpreted from the start of the transect lines (nearshore) to a distance of 60 km from the start of the transect line (offshore). The median transect displays Chl a concentrations between (2.0-0.2 mg m^{-3}) transect 1(1.75-0.2 mg m^{-3}), transect 2 (1.0-0.2 mg m^{-3}), transect 3 (3.0-0.2 mg m^{-3}), transect 4 (2.2-0.2 mg m^{-3}), and transect 5 (2.0-0.5 mg m^{-3}).

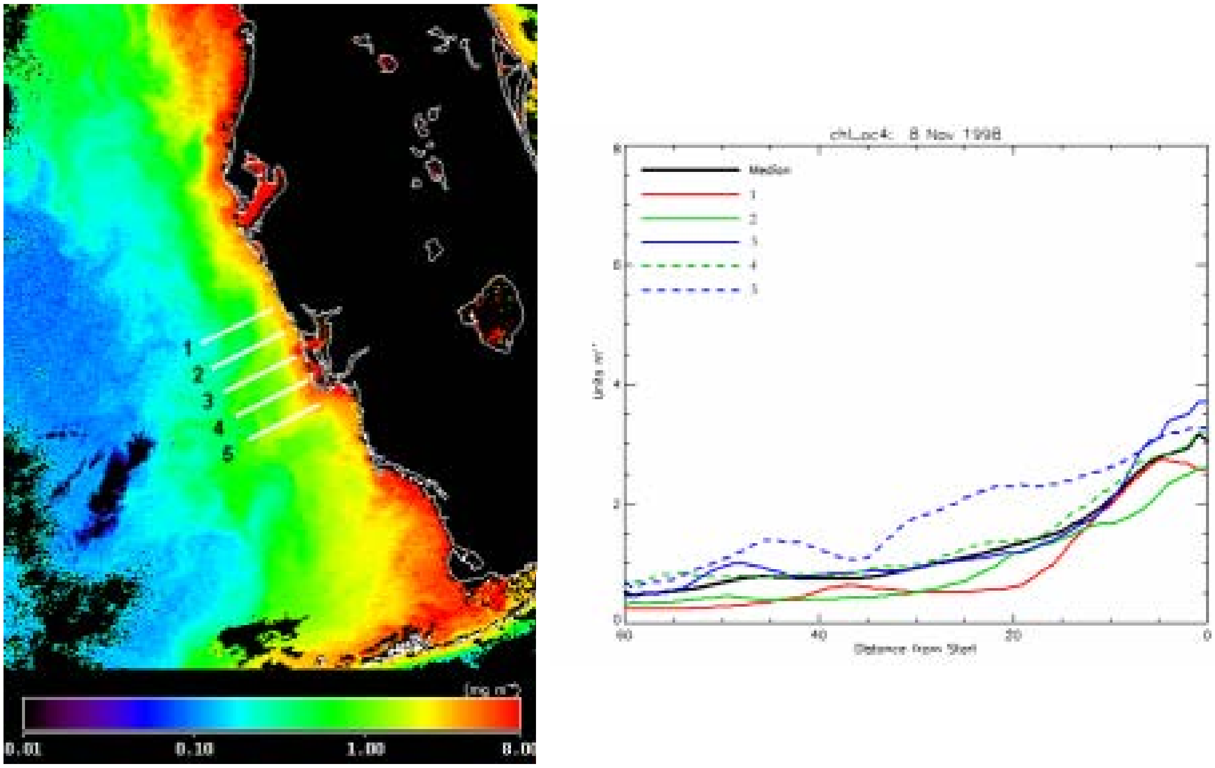

Figure 5. SeaWiFS estimated chlorophyll a concentration for the West Florida Shelf and selected transects on November 1, 1998. Just after Tropical storm Mitch, higher concentrations of chloropyll a are present in the region of the barrier islands surrounding Charlotte Harbor (~8.0 mgm^{-3}) with decreasing concentration further offshore. The WFS has been divided into 5 parallel transects for analysis. These transects are interpreted from the start of the transect lines (nearshore) to a distance of 60 km from the start of the transect line (offshore). The median transect displays Chl a concentration readings between (3.0-0.5 mg m^{-3}) transect 1(2.5-0.3 mg m^{-3}), transect 2 (2.5-0.3 mg m^{-3}), transect 3 (3.75-0.5 mg m^{-3}), transect 4 (3.25-0.75 mg m^{-3}), and transect 5 (3.25-0.75 mg m^{-3}).

However, the predicted $R_{rs}(412)$ and $R_{rs}(443)$ values are not as satisfying to review (Figures 6 and 7). While it appears that we may have achieved an adequate representation of the increase in biomass (and CDOM, see N00014-00-1-0411), the remote sensing reflectance values are obviously much lower and appear to change off-shore/on-shore relationship between November 1st and November 8th. The lower values can sometimes be attributed differences in illumination inputs to the radiative transfer calculations. However, the change in the off-shore/on-shore gradient on November 8th suggests that something fundamental may be different between our simulated IOPs and the resultant R_{rs} values, versus those estimated from SeaWiFS. One can speculate that since a tropical storm just passed through the region, a tremendous amount of sediments may have been re-suspended, adding a significant backscattering component that was not incorporated into the ES2 simulation. This would appear plausible since both the OC4 Chlorophyll a algorithm (Figure 5) and the Carder $a_{dg}(412)$ (Figure 2 of N00014-00-1-0411) algorithm both suggested increases in the near-shore following the storm, even while the absolute magnitude of the spectral R_{rs} values are increasing. It does appear that this scattering effect has dissipated by December 4th (Figure 8, 9, and 10) and a better correlation between the off-shore/on-shore gradient in predicted and measured R_{rs} is found. However, the

magnitude of the predicted R_{rs} values is still much too low, suggesting a problem with the scattering sections of combined ES2/Ecolight system. A further exploration of these results is anticipated in FY2003.

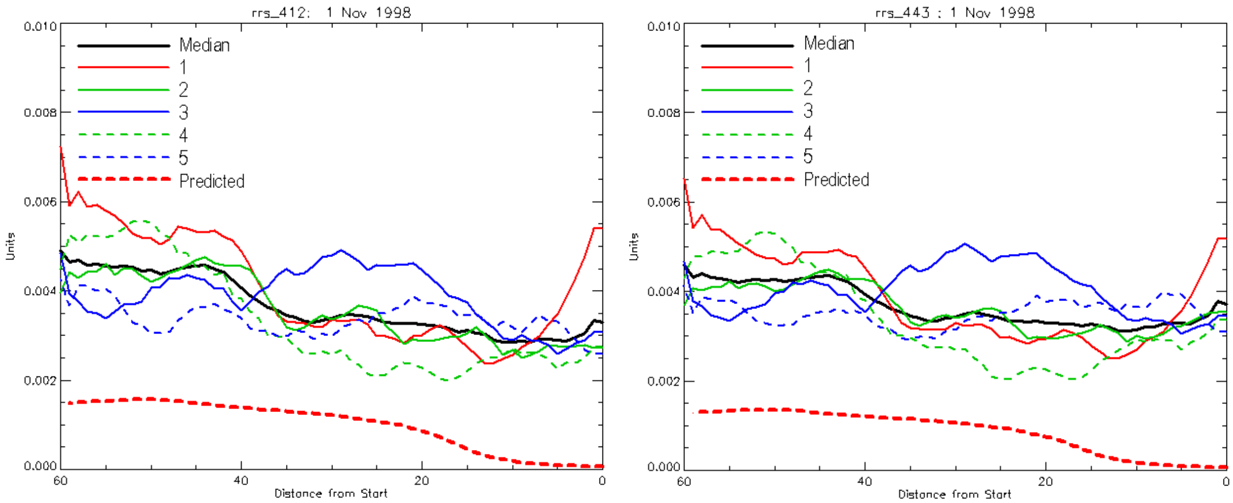

Figure 6. SeaWiFS estimated and ES2 predicted R_{rs}(412) and R_{rs}(443) for the West Florida Shelf and selected transects (see Figure 4) on November 1, 1998. ES2 predicted Rrs (412)and (453) are significantly lower than the median Rrs estimated from SeaWiFS.

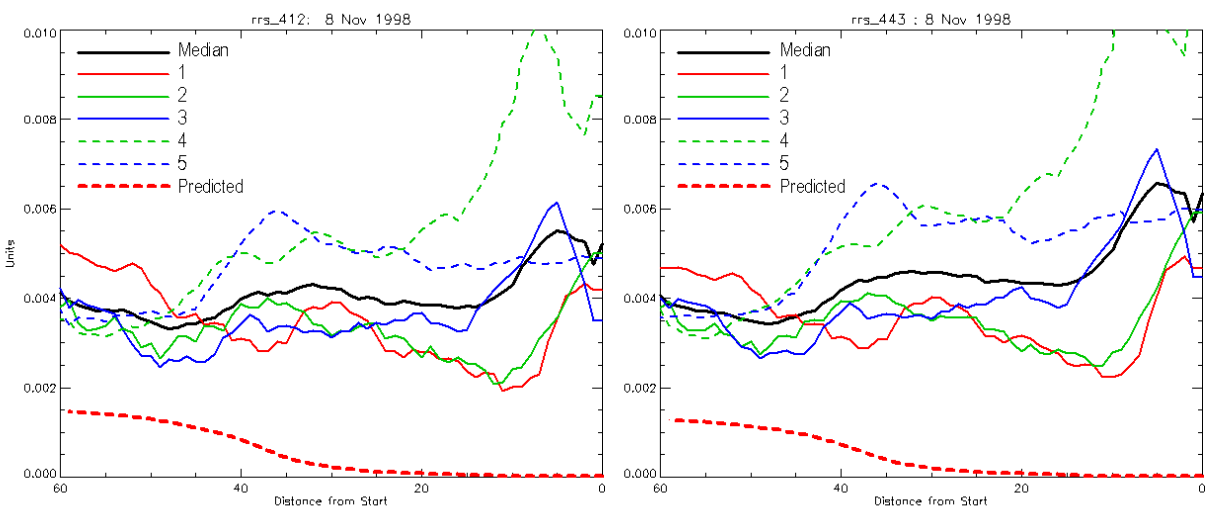

Figure 7. SeaWiFS estimated and ES2 predicted R_{rs}(412) and R_{rs}(443) for the West Florida Shelf and selected transects (see Figure 4) on November 8, 1998. ES2 predicted Rrs (412)and (453) are significantly lower than the median Rrs estimated from SeaWiFS. There appears to be a change from an offshore to a nearshore Rrs signal from November 1 to 8 that appears to result from a increase in scattering relative to absorption. This effect is not well simulated by EcoSim.

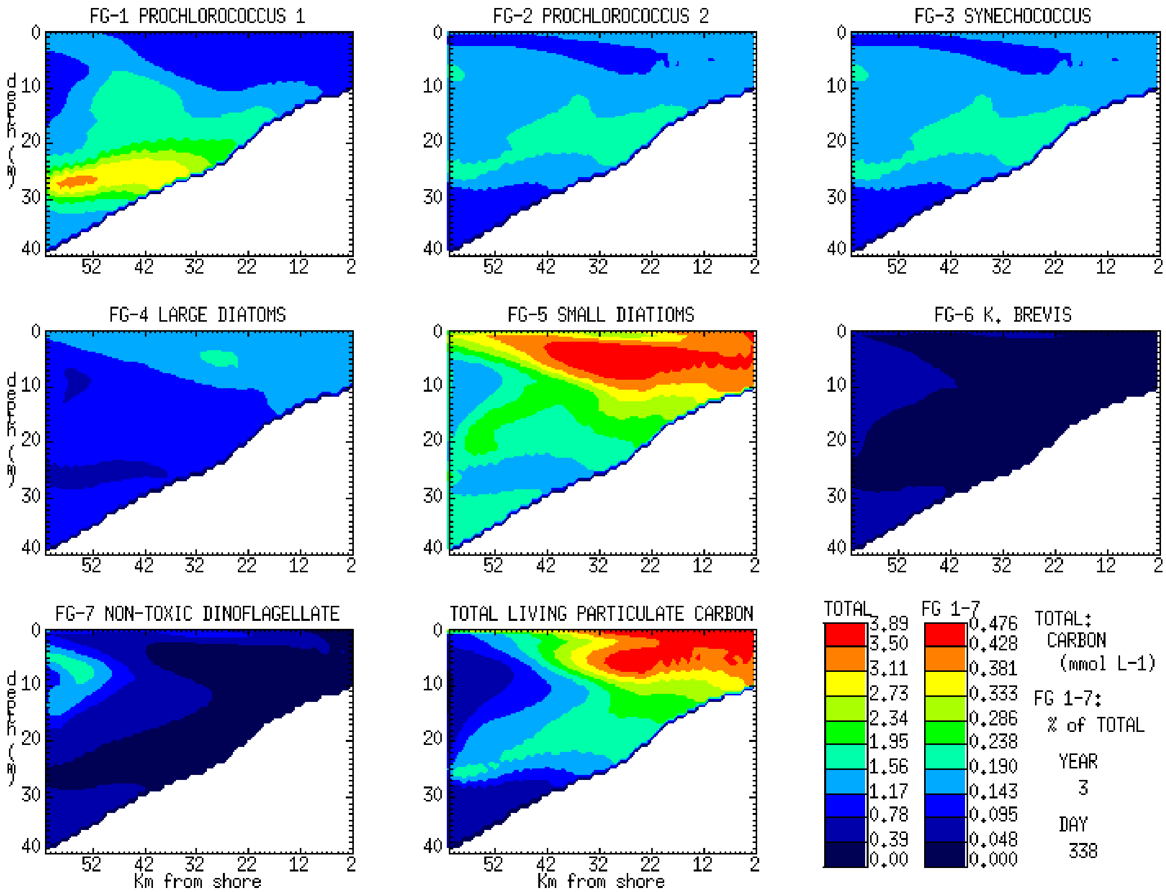

Figure 8. Predicted chlorophyll and functional group distribution for day-of-year 335 (December 5th). Prochlorococcus and Synechococcusare are present offshore (>32km from shore at a depth of ~20-30m). This region is mostly dominated by Prochlorococcus. Large and small diatoms are present nearshore, (~2-52km from shore and at a depth of ~0-15m). This region is almost entirely dominated by small diatoms. K. brevis is not present on the WFS. Non-toxic dinoflagellates are present offshore (>52km from shore and at a depth of ~0-15m). Total living particulate carbon is greatest in shallow nearshore waters (<32km from shore at a depth of <20m).

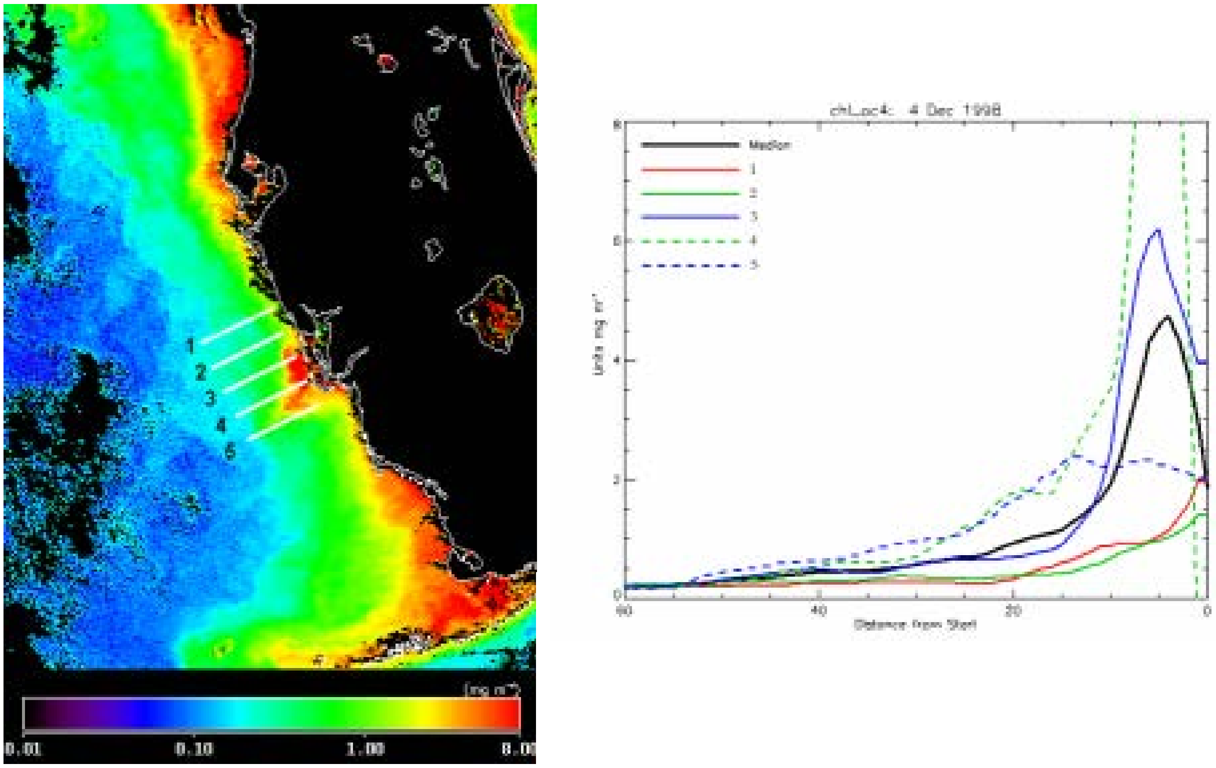

Figure 9. SeaWiFS estimated chlorophyll a concentration for the West Florida Shelf and selected transects on December 4, 1998. High concentrations of chloropyll a are present in the region of the barrier islands surrounding Charlotte Harbor (~8.0 mgm^{-3}) with decreasing concentration further offshore. The peak Chl a signal has moved further offshore of the barrier islands. The WFS has been divided into 5 parallel transects for analysis. These transects are interpreted from the start of the transect lines (nearshore) to a distance of 60 km from the start of the transect line (offshore). The median transect displays Chl a concentration readings between (5.0-0.2 mg m^{-3}) transect 1(2.0-0.2 m gm^{-3}), transect 2 (1.5-0.2 m gm^{-3}), transect 3 (6.2-0.2 m gm^{-3}), transect 4 (>8.0-0.2 m gm^{-3}), and transect 5 (2.25-0.2mg m^{-3}).

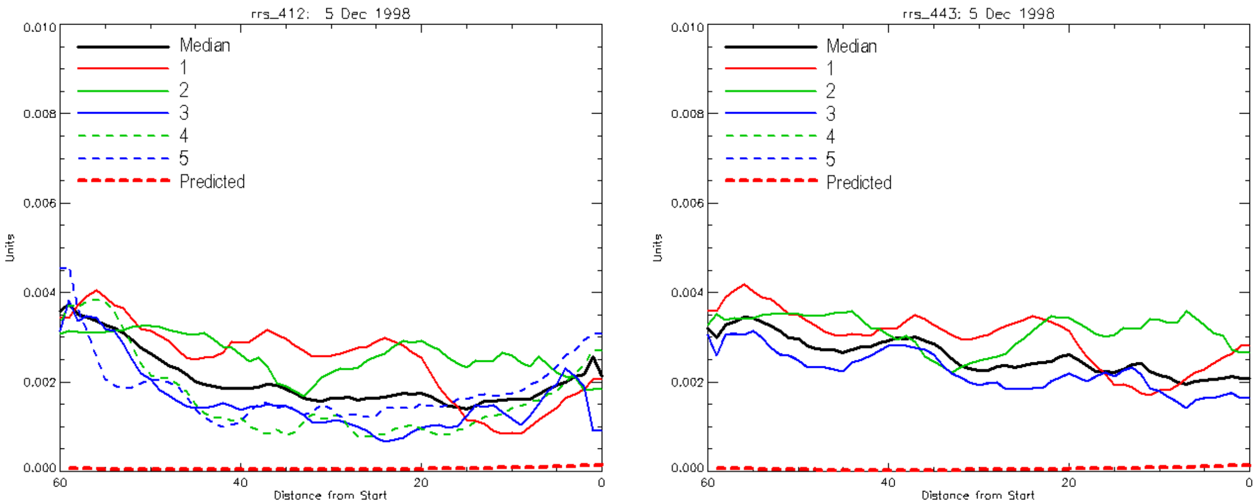

Figure 10. SeaWiFS estimated and ES2 predicted R_{rs}(412) and R_{rs}(443) for the West Florida Shelf and selected transects (see Figure 4) on December 4, 1998. ES2 predicted Rrs (412)and (453) are significantly lower than the median Rrs estimated from SeaWiFS. There appears to be a slight nearshore Rrs signal on December 4, suggesting that the increased scattering to absorption signal from the tropical storm has subsided.

IMPACT/APPLICATIONS

Forecasting IOPs over operational time horizons of 5 to 10 days will require the ability to directly compare predictions of water-leaving radiance to the data most likely to be used for initialization and validation of the predictions, i.e., aircraft and satellite hyperspectral remote sensing data. This effort will yield a simulation ready to begin direct data assimilation of the water column optical properties to predict absorption and scattering over short-term time horizons.

TRANSITIONS

The EcoSim 2.0 and Ecolight 4.1 are being developed as open source code and are accessible to any investigators interested in predicting IOPs and water-leaving radiance.

RELATED PROJECTS

We are collaborating with Dr. C. Mobley of Sequoia Scientific, Inc for the coupling of EcoSim with Hydrolight, and Drs. R. Arnone, NRL, and K. Carder, USF, for satellite data analysis, and Drs. C. Davis and J. Bowles, NRL, for hyperspectral aircraft data collection and analysis.

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